FACTORS INFLUENCING THE LIKELIHOOD OF INITIATION OF INTERNAL EROSION THROUGH AN EMBANKMENT DAM				**DATE: JULY 2012**
Factor	**Influence on Likelihood / Relative to Reclamation Historical Base Rates (see notes)**			**Comments**
	Less Likely	**Neutral**	**More Likely**	
Seepage Presence of seepage Seepage fluctuations	 No seepage (low probability for a concentrated leak) Long-term steady rate of seepage unrelated to reservoir level	 Insignificant seepage; or seepage possible but unseen Seepage fluctuates with reservoir, but at a predictable rate	 Seepage significant Seepage is increasing over time at the same reservoir level; or seepage is episodic or surging	The presence or absence of seepage may not be known with certainty. Episodic seepage could be an indicator that an internal erosion pathway is repeatedly opening and closing. Evidence of material transport in seepage flow would indicate near certainty that erosion is occurring.
Soil Erodibility (adapted from Sherard, 1953)	Well-graded material with clay binder, (10<PI<15), well or poorly compacted Much less likely if plastic clay, PI > 15, well or poorly compacted	Well-graded, low plasticity material, (6<PI<10), well or poorly compacted	Well-graded, cohesionless material, (PI<6), well or poorly compacted Uniform, fine cohesionless sand, (PI<6), well or poorly compacted	Sherard's guidance is intended to represent the relative erodibility of a range of soil types with different PI and different compaction efforts. **Use this guidance in conjunction with base rate statistics such as *87% of Reclamation incidents were in soils with PI< 7.*** Dispersive soils are not included here; dispersive soils can be much more erodible and rates of initiation should be adjusted to reflect dispersion potential.
Cracks – located on the crest, or in test pits that expose the upper part of the impervious zone.	No cracking observed when large areas, or all, of the top of the core is exposed	No cracking observed on the crest or in limited test pits exposing the core.	Transverse cracks on the surface of the core and/or, extensive, open longitudinal cracking. Much more likely for transverse cracks that extend across the core, and extend below reservoir water level being considered	At Reclamation it has not been standard practice to excavate test pits at the crest of the dam to expose the impermeable zone. Therefore, the potential for cracking generally relies on observations of cracks at or near the crest, and on other factors (in this table) that could increase or decrease the potential for cracking.
Sinkholes or depressions	No observations of sinkholes or depressions, including on upstream slope areas that are normally submerged.	Minor depressions on the upstream or downstream slopes that developed slowly and do not change over time.	Observations of sinkholes or depressions on the crest, upstream slope, or downstream slope that appear suddenly or change with time.	Sinkholes and depressions are important observations but are not always associated with an internal erosion potential failure mode. Localized settlement of limited loose zones in the embankment could result in sinkholes or depressions. Wave action on riprap can also create localized depressions. If sinkholes or depressions are observed, look for nearby conduits, toe drains, coarse graded materials or other anomalies that could allow for material transport. Sinkholes and depressions could result from seepage through internally unstable soils that allow material

FACTORS INFLUENCING THE LIKELIHOOD OF INITIATION OF INTERNAL EROSION THROUGH AN EMBANKMENT DAM				DATE: JULY 2012
Factor	**Influence on Likelihood / Relative to Reclamation Historical Base Rates (see notes)**			**Comments**
	Less Likely	**Neutral**	**More Likely**	
				transport to occur.
Loose or soft zone within the impervious zone	Cone penetration tests, or continuous sampling, show no loose or softened zones	No investigations	Softened or loose zones detected by drilling and sampling of the impermeable zone	Use caution, follow appropriate guidelines and work with an experienced engineering geologist when drilling and sampling in an embankment dam.
Construction (also see general quality of construction below) Compaction equipment Compaction density and moisture	Material compacted with appropriate equipment, with well-documented quality control test results Compacted to greater than 98% Standard Proctor dry density; 0 to +2% of optimum water content	Material compacted with appropriate equipment Compacted to 95-98% Standard Proctor dry density; -2% to +2% of optimum water content	Material compacted by dozer or "equipment travel;" no specific compaction by rollers; Much more likely for materials placed and spread by horse with no formal compaction. Poorly compacted; dry of optimum water content	Poor compaction can result in a low density and high permeability zone through the embankment. Judgment is necessary when evaluating construction – material compacted in thin lifts with horse drawn and water conditioning may be well-compacted. Compaction and density ranges stated are for general guidance purposes.
Impermeable zone width	Homogeneous earthfill dam; zoned earthfill with very wide impervious zone with relatively flat slopes. Ratio of reservoir head to width of core (both measured at a potential location of internal erosion) less than 1.	Zoned earthfill with wide impervious zone. Ratio of reservoir head to width of core (both measured at a potential location of internal erosion) between 1 and 2.	Zoned earth or rockfill dam with a narrow core. Ratio of reservoir head to width of core (both measured at a potential location of internal erosion) greater than 2.	Greater widths of impermeable zones make it less likely for a continuous defect (e.g. crack or high permeability zone) to form. Many Reclamation dams were built with a wide impervious zone.
Differential settlement of foundation (also see differential settlement due to closure section)	Rock foundation or soil foundation with consistent low compressibility.	Shallow soil foundation, or soil foundation with gradual variation in thickness and compressibility.	Soil foundation adjacent to rock foundations; variable depth and compressibility of foundation soils. Firm compacted soils adjacent to loose, compressible foundation soils. Much more likely if collapsible soils (loess; weakly cemented soils) are present. Also much more likely if localized, deep compressible soils are within less compressible soils.	Differential settlement can occur anywhere two adjacent materials with different compressibility characteristics are located. (e.g. rock and soil; firm backfill of diversion channel or conduit through looser foundation, etc.). Differential settlements can lead to cracking in low stress zones.
Foundation profile under the impermeable zone (also see slope of abutments)	Uniform foundation profile, gradual abutment slopes; absence of terraces, steps or benches	Profile has some, but not extreme undulations and variability. Might include a wide bench in the bottom half of the dam; or narrow bench in the upper half of the dam; gradual excavation slopes adjacent to benches	Profile has abrupt changes; especially if abrupt changes are in the upper half to third of the embankment; wide terraces or benches adjacent to steep excavations. Much more likely if terraces or benches are continuous across the core/ impermeable zone.	Adverse shaped foundation profiles can cause low stress zones, differential settlement and cracking. Haul roads and grouting platforms can result in horizontal, upstream to downstream benches.

FACTORS INFLUENCING THE LIKELIHOOD OF INITIATION OF INTERNAL EROSION THROUGH AN EMBANKMENT DAM				DATE: JULY 2012
Factor	**Influence on Likelihood / Relative to Reclamation Historical Base Rates (see notes)**			**Comments**
	Less Likely	**Neutral**	**More Likely**	
Settlement (during construction and post construction, as percentage of embankment height)	Approx. 1% or less during construction. Approx. 0.25% or less post-construction.	Approx. 1-3% during construction. Approx. 0.25% - 1% post construction.	Approx. 3-5% during construction. Approx. 1-2% post construction. Much more likely for settlements greater than 5% during construction. Much more likely for post construction settlement greater than 2%.	Other considerations for settlement include the duration over which the settlement has occurred, and location of settlement (crest, upstream slope, downstream slope). Differential settlement between different points across the dam should be considered, particularly if differential settlement locations align with foundation profile changes or changes in foundation material compressibility. This guidance is from Fell, Wan and Foster (2004) and is based on work by Hunter and Fell (2003).
Foundation preparation of surface irregularities (foundation of the impermeable zone) and construction of first lifts on foundation	Uniform rock surface, or rock surface treated with dental concrete or shotcrete; foundation shaping to remove irregularities; special compaction of the first several lifts of impermeable material on rock; impermeable materials at the contact have at least moderate plasticity, maximum particle size < 3 inches; gradation not subject to segregation. Alternately, a uniform well-compacted, dense, low permeability soil foundation.	Irregular rock surface with minimal treatment and shaping; or untreated undulating rock surface without significant irregularities; little or no special compaction of the first lifts of impermeable materials on rock; impermeable materials at the contact have low plasticity. Alternately, a compacted soil foundation.	Highly irregular, untreated, rock surface with no shaping or treatment; no special compaction of the first lifts of impermeable materials on rock; impermeable materials at the contact are non-plastic; Broadly-graded impermeable materials that could have segregated or may be internally unstable. Alternately, an irregular or benched soil foundation with light or no compaction. Much more likely if a rock foundation surface was blocky and included loose rock.	Inadequate foundation preparation could result in a high permeability zone, low stress zone or other transverse defect causing a concentrated leak along the embankment/ foundation contact. This factor may be more relevant to PFMs related to the foundation, but foundation irregularities could cause embankment defects deep in the dam.
Slope of abutments (also see foundation profile)	Gentle abutment slope, generally 30 degrees (from horizontal) or less	Moderate abutment slope, approximately 30-45 degrees (from horizontal)	Steep abutment slope, generally greater than 45 degrees (from horizontal); Much more likely if abutment slopes are greater than 60 degrees.	In general, steeper abutment slopes would tend to promote greater differential settlements over shorter distances, which could lead to cracking or low stress zones. The influence of abutment slope should be evaluated along with the foundation profile and the influence of benches, terraces or abrupt changes in geometry. For very steep abutments and a narrow valley, “arching” of the soils across the valley can lead to horizontal transverse cracking and low stress zones.

Factors Influencing the Likelihood of Initiation of Internal Erosion Through an Embankment Dam				**Date: July 2012**
Factor	**Influence on Likelihood / Relative to Reclamation Historical Base Rates (see notes)**			**Comments**
	Less Likely	**Neutral**	**More Likely**	
Differential settlement due to closure section construction	No closure section through the embankment (off stream dam or river diverted using outlet works, tunnel, or other means).	Well-built closure section.	Closure section that may have remained open for several construction seasons; construction on compressible soils leading to differential settlements between existing fill and closure fill; change in borrow source or change in material characteristics; little or no quality control with the possibility that disturbed materials were not removed. Rapid construction of closure section.	Unique stress and settlement behavior may be associated with closure sections, which may have different material types and rapid construction. A well-built closure section would be characterized by: good design and construction details that provide a good bond between existing fill and closure fill; flat side slopes; built on firm materials; no substantial change in borrow material characteristics; careful quality control with good base soil preparation including excavation and replacement of disturbed materials.
Seasonal shut-down	No seasonal shut down and no fill placement during freezing weather. Weather and fill placement schedule well documented.	Seasonal shut down or potential for placement during freezing weather, with good documentation of fill being removed or treated, moisture conditioned, re-compacted and tested before commencing with additional fill placement.	One or more seasonal shut downs for an extended period; frozen / disturbed materials not removed, surface not treated before commencing fill placement; or lack of documentation of removal / treatment. Much more likely if there is documentation of frozen fill that was not removed or treated.	Seasonal shut-down or fill placement in freezing weather can lead to a high permeability zone through the dam.
Embankment zoning and overall geometry	Wide homogeneous earthfill dam or zoned earthfill dam with zones that have similar deformation characteristics; Earthfill dam with filters and drains with similar deformation characteristics.	Wide homogeneous earthfill dam with limited zones with varying deformation characteristics; Zoned earthfill dam with filters and drains with varying deformation characteristics. Central core rockfill dam with compacted core and rockfill, with core stiffness greater than or equal to that of the rockfill.	Central core earth and rockfill with uncompacted rockfill or rockfill placed in large lifts; Central core earth and rockfill with narrow core of lower modulus than filters and rockfill. Consider relative width of the core compared to the rockfill zones and the potential for “hang up” or arching of the core between stiffer filter and rockfill zones.	In general, zoning of an embankment dam is beneficial for seepage control; however, this factor considers the potential for variable deformation behavior due to different material types and compaction amounts that might lead to differential settlement, cracking or low stress zones.
General quality of construction and quality control (also see construction as related to compaction above)	Good clean-up and preparation of any wet, dry, or frozen surfaces during construction. Good supervision and quality control. Complete, well-documented records that confirm the high quality construction.	Good clean-up and preparation of any wet, dry, or frozen surfaces during construction. Good supervision and quality control. Some detailed records and documentation.	Poor clean-up after wet, dry, or frozen periods during construction. Intermittent supervision and quality control. Much more likely if there was no or poor supervision and quality control.	Embankment lift surfaces left to dry and crack could result in concentrated leaks. Wet or frozen zones left in the dam could result in high permeability zones or differential settlements. In general, Reclamation dams have been constructed with good supervision, quality control and documentation; however, a detailed

Factors Influencing the Likelihood of Initiation of Internal Erosion Through an Embankment Dam				**Date: July 2012**
Factor	**Influence on Likelihood / Relative to Reclamation Historical Base Rates (see notes)**			**Comments**
	Less Likely	**Neutral**	**More Likely**	
				examination of quality control records may be needed to reveal additional details beyond the generalizations (averages) often published in construction reports.
Lift thickness (of impermeable material)	Same as for "neutral" but with complete, well-documented records that confirm the lift thickness was controlled.	Lift thickness 8-10 inches loose (6-8 inches after compaction). Few detailed records and little documentation.	Lift thickness at the limit of compaction equipment (e.g. ~ 15 inches loose). No documentation. Much more likely if lift thickness beyond the limit of compaction equipment (e.g. > 18 inches); or no control on lift thickness.	Loose lifts or uncompacted zones can result in a high permeability zone and concentrated leak through the dam.
Impermeable material characteristics	Same as for "neutral" but with complete, well-documented records that confirm material characteristics.	Low variability of material particle size, not subject to segregation, insitu borrow material at or near optimum water content; good moisture conditioning in the borrow area and/or on the fill.	Some variability in material particle size, some potential for segregation; insitu borrow material dry of optimum water content; moderate moisture conditioning on the fill. Much more likely with large variability of material particle size, broadly graded soils subject to segregation or internal instability; borrow materials significantly dry of optimum water content in borrow area, with poor moisture conditioning	
Desiccation cracking	Low plasticity core, temperate climate; pavement and/or other zones over core of sufficient thickness to prevent desiccation	Low to medium plasticity core, seasonally dry or temperate climate; pavement and/or other zones over core of sufficient thickness to prevent desiccation	Medium to high plasticity core, seasonally dry and hot climate, no pavement or other material over core; or insufficient thickness to prevent desiccation.	Applies to core, or impermeable zone for homogeneous dams.
Instrumentation details in the core / impervious zone	No instrumentation in the impervious zone	Some instrumentation (cables or piezometers) passing through the core; but designed and constructed with appropriate details.	Instrumentation (cables or piezometers) passing through the core; but lack of appropriate details. Upstream to downstream penetrations through the core are more of a concern than vertical penetrations.	Appropriate design and construction details would include placement and good compaction of plastic impervious materials around instruments, cables or other penetrations.
Reservoir operation	Steady operational levels	Operational levels cycle annually, reaching the normal maximum operational level during most years. Reservoir level increases at a relatively slow, steady rate.	Reservoir has never reached the normal maximum operational level; or reservoir operates well below the normal maximum level for years and reaches the normal maximum level infrequently. Reservoir level increases rapidly, or reservoir level is "flashy."	Soils in embankment dams strain in response to changes in stresses associated with reservoir level changes. Slower rates of change allow embankments to deform slowly in response to change, decreasing the chance of a crack or low stress zone.

FACTORS INFLUENCING THE LIKELIHOOD OF INITIATION OF INTERNAL EROSION THROUGH AN EMBANKMENT DAM				DATE: JULY 2012
Factor	**Influence on Likelihood / Relative to Reclamation Historical Base Rates (see notes)**			**Comments**
	Less Likely	**Neutral**	**More Likely**	
Extensive vegetation, root balls, rodent holes	No trees or vegetation, no root balls, no evidence of rodents.	Limited vegetation that is controlled before root systems become extensive. Limited rodent activity primarily in downstream shell zones away from the impermeable zone.	Large trees in the groins, on the crest or on the downstream slope; certain vegetation with extensive root systems; stumps with decaying root systems. Rodent holes, particularly those of large rodents that excavate dens in embankments when the reservoir is low.	Vegetation, root systems and rodent holes can increase the gradient within a dam by short-cutting seepage paths. The extent of damage caused by rodents may not be realized until the reservoir rises. The significance of rodent burrows depends on the size of the embankment.
Age of dam / length of service	In service greater than 20 years, reaching the normal maximum water surface elevation almost every year.	In service 5- 20 years, reaching the normal maximum water surface elevation most years.	Newer dam, in service less than 5 years; Alternatively, older dam that has not been tested to up to the normal maximum water surface elevation.	Reclamation and world-wide statistics indicate incidents are more likely to occur in the first few years of reservoir operation. However, those statistics reflect many historical incidents with older dams, and one could argue that modern designed and constructed dams are less likely to have first filling incidents. **In addition, evidence suggests that internal erosion incidents can develop at any age.**

Notes on use of Table:

1. Table is intended to provide guidance in addition to historical base rates of initiation of internal erosion. The neutral factors listed in the table would correspond to average base rates. Neutral factors do not imply a 50% probability. In general for a given Reclamation dam, there would be justification to select a probability of initiation of internal erosion higher than historical base rates if that dam was characterized by multiple “more likely” factors listed above; and conversely, there would be justification to select a probability of initiation of internal erosion lower than historical base rates if that dam was characterized by multiple “less likely” factors. Whether the estimated probability of initiation of internal erosion is higher, lower or near the historical base rate, the justification for the estimated probability must be documented. This table provides some guidance for that justification.

2. Some factors listed on the table apply to all internal erosion mechanisms (backward erosion piping, internal migration, scour, suffusion/suffosion) while some factors might only apply to one mechanism.

3. Some factors listed on the table are more critical to initiation of internal erosion than others. In general, more influential factors are listed towards the top of the table and less influential factors are listed towards the bottom.

4. For some factors, the “More likely” column also includes factors that would make the probability of initiation “much more likely.”

5. Expert guidance is critical for interpreting observations at a dam and making judgments that relate performance of a specific dam to historical base rates of internal erosion.

References:

Draft Risk Analysis Methodology Appendix E (2000), Estimating Risk of Internal Erosion and Material Transport Failure Modes for Embankment Dams, version 2.4, Bureau of Reclamation, Technical Service Center, Denver, CO. August 18, 2000. (This document was never finalized; it was superseded in 2008 by Dam Safety Risk Analysis Best Practices Training Manual, Chapter 24.)

Fell, R., C.F. Wan, and M. Foster (2004), "Progress Report on Methods for Estimating the Probability of Failure of Embankment Dams by Internal Erosion and Piping," University of New South Wales, Sydney, Australia. UNICIV Report 428. 2004.

Hunter, G. and Fell, R. (2003). The Deformation Behaviour of Embankment Dams. UNICIV Report No. R-416. ISBN: 0077-880X, School of Civil and Environmental Engineering, The University of New South Wales.

Sherard, J.L. (1953), "Influence of Soil Properties and Construction Methods on the Performance of Homogeneous Earth Dams," Technical Memorandum 645, Bureau of Reclamation, Denver, Colorado.